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Are we purveyors of wetland homogeneity? A model of degradation and restoration to improve wetland mitigation performance

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Abstract

The national goal of no net loss of wetland functions is not being met due to a variety of suboptimal policy and operational decisions. Based on data used to develop a conceptual model of wetland degradation and restoration, we address what can be done operationally to improve the prospects for replacing both the area and functions of mitigated wetlands. We use measures of hydrologic, soil, and biodiversity characteristics from reference standard sites, degraded wetlands, and created wetlands to support our premise. These data suggest that wetland diversity and variability often become more homogeneous when subjected to a set of stressors. The degradation process reduces the original heterogeneity of natural wetlands. In addition, soil characteristics and composition of biological communities of creation projects may mirror those of degraded wetlands. We recommend that scientists and managers use identical sampling protocols to collect data from reference wetlands that can be used to assess the condition of degraded wetlands and to improve the design and performance of mitigation projects.

Keywords: Wetlands; Restored wetlands; Created wetlands; Mitigation; Reference sites

1. Introduction

1.1. Wetland mitigation policy and practice

The U.S. Environmental Protection Agency's Office of Wetlands, Oceans, and Watersheds established two national priorities for wetlands in 2000: for states and tribes to develop wetland monitoring programs, and to improve the success rate of compensatory mitigation

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(D. Vetter, personal communication). In 2002, federal resource agencies released a National Wetlands Mitigation Action Plan (U.S. Army Corps of Engineers, 2002) designed to improve the ecological performance of compensatory wetland mitigation. The Action Plan acknowledged the critical evaluations of wetland mitigation performance by the National Research Council (NRC, 2001) and the U.S. General Accounting Office (2002), and affirmed a commitment to a goal of no net loss of wetlands through improved accountability, monitoring, and research. Clearly, there is a renewed and strong commitment to assessing and restoring wetlands as regulated "waters of the U.S.", and to do so on a watershed basis (e.g., http://www.epa.gov/owow/). The prospects for comprehensive wetlands monitoring, assessment, and mitigation have never been stronger, either from regulatory or technical perspectives. As stated by the National Research Council (NRC, 2001), the goal of no net loss of wetland functions is not being met due to a variety of suboptimal policy and operational decisions. In this paper, by way of a conceptual model of wetland degradation and restoration, operational decisions that can greatly improve the prospects for replacing both the area and functions of wetlands are addressed.

There are two primary reasons to engage in wetland restoration and creation projects. To comply with environmental regulations, there is an expectation of compensatory mitigation for losses of wetland area or function. Losses to wetlands that occur as a result of a permitting process usually are required to be mitigated. Typically, this mitigation results in a project designed to replace at least the same amount of wetland area impacted. Replacement of specified functions originally provided by that impacted wetland also might be required. Implementing the project becomes a condition of the issued permit.

Outside the regulatory arena, an interested group or person elects to design and implement a project that is perceived to increase or enhance wetland resources (NRC, 1992). These types of projects are usually initiated voluntarily. In either case, each project proceeds through a series of steps that includes selection of a suitable site, acquisition or gaining access to the chosen site, development of conceptual designs, preparation of construction specifications and implementation plans, and eventual construction of the wetland (Brooks, 1993). Post-construction monitoring may or may not be required or occur.

The degree to which wetland restoration and creation projects achieve some measure of success has received considerable debate (Kusler and Kentula, 1990; Brooks, 1993; Brinson and Rheinhardt, 1996; Mitsch and Wilson, 1996; Cole et al., 1997a; Zedler and Callaway, 1999). Proponents tout the potential benefits, real or perceived, of increasing wetland area and function toward an overall net gain in the resource. Opponents argue that mitigation is a license to impact natural wetlands, and that the resultant projects have scant resemblance to the wetlands they are supposed to replace.

1.2. A model of wetland degradation and restoration

Based on comparative studies of reference and created wetlands (e.g., Bishel-Machung et al., 1994; Cole and Brooks, 2000; Campbell et al., 2002) and our collective experience of comparing reference wetlands from a range of hydrogeomorphic (HGM) subclasses along a disturbance gradient (e.g., Cole et al., 1997b; Wardrop and Brooks, 1998; O'Connell et al., 2000; Brooks, 2004; Brooks et al., 2004), we are proposing a conceptual model of wetland degradation and restoration as a set of testable hypotheses. We challenge scientists and managers to examine our model, test the associated hypotheses, and if valid, make the necessary adjustments to reduce further degradation of natural wetlands and to improve the performance of wetland restoration and creation projects.

The conceptual model, presented schematically in Fig. 1, recognizes a degradation process caused by one or more stressors. The typical range of stressors affecting wetlands was summarized by Adamus and Brandt (1990) and expanded by Adamus et al. (2001). The cumulative effects of any combination of these stressors appear to result in a convergence of characteristics producing a more homogeneous group of wetlands. In turn, those degraded wetlands are most similar to created sites.

1.3. Hypotheses

Our four related hypotheses are:

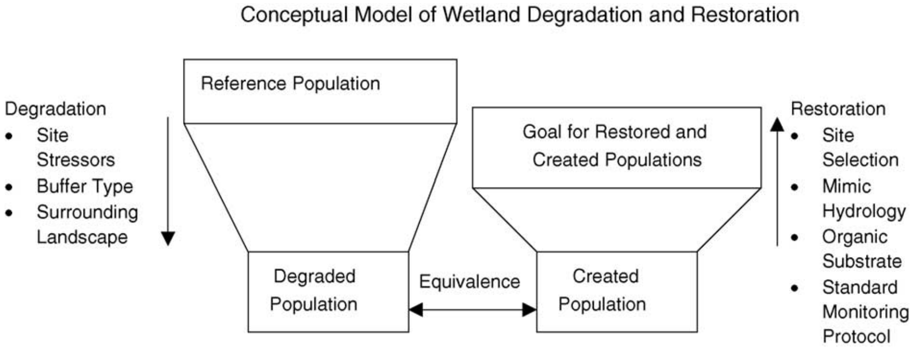

Fig. 1. Model of wetland degradation and restoration showing the equivalence of degraded and created population characteristics, and the goal of mimicking reference wetlands with mitigation projects.

1. Wetlands change in structure and function when subjected to one or more stressors resulting in a recognized degradation sequence
   The ultimate form of degradation is complete loss of areal extent (e.g., fill or dewatering) at which time the wetland ceases to exist in that location. Inventory trend data have been reported primarily with regard to changes in areal extent (e.g., Dahl, 1990). Much more widespread, yet more difficult to quantify, has been the degradation of wetlands, defined as loss of functional performance. The application of HGM assessment models or similar approaches provides a means to quantify loss of wetland function (Brinson, 1993; Rheinhardt et al., 1999).
2. Degraded wetlands develop characteristics that differ from reference standard sites that can be expressed as a change in condition
   One option in wetland mitigation is to create replacement wetlands. Questions have been raised about whether created wetlands are equivalent in structure and function to the natural wetlands they replace (Zedler and Callaway, 1999). Galatowitsch and van der Valk (1994) stated that the definitive test of mitigation success was how well restored wetlands resemble natural wetlands; the same could be said of created sties. Our findings (Bishel-Machung et al., 1994; Cole and Brooks, 2000; Campbell et al., 2002) agree with general statements made by NRC (2001) that created wetlands may never express the full range of ecological variability found in natural wetlands. Many created and restored sites are far wetter than natural wetlands, with extensive areas of open water.
3. Substantial improvements in structural and functional performance of created and restored wetlands can occur if data from reference wetlands are used to design mitigation projects and to evaluate their success
   It is imperative that criteria derived from studies of reference wetlands be used in the design, construction, and evaluation of mitigation projects. In addition, to optimize the use of data through the assessment, design, and evaluation processes, consistent use of a consistent sampling protocols when comparing among natural wetlands and projects is essential (e.g., Gray et al., 1999; Wardrop et al., 2004).
4. A wetland mitigation project can match the structure and function of a reference wetland in a comparable HGM subclass for a given ecoregion
   We do not believe that exact replication of natural wetland ecosystems is possible, but we should aspire to approach the goal of replicating structure and function using the best possible designs and construction methods based on the best possible science derived from studies of reference wetlands and other experimental work. This assumes, of course, that current or historical data from reference sites can be acquired.

2. Methods

The use of reference sites has become increasingly more common as ecologists and managers search for reasonable and scientifically based methods to measure

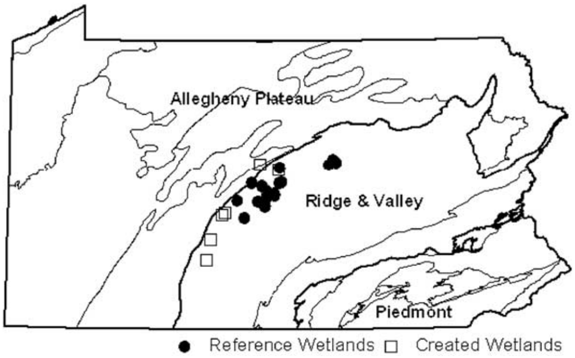

Fig. 2. Locations of reference wetlands and created wetlands compared in Pennsylvania.

and describe the inherent variability in natural aquatic systems (Hughes et al., 1986; Kentula et al., 1992; Brinson, 1993; Rheinhardt et al., 1999). Although reference sites often represent areas of minimal human disturbance (i.e., reference standards in HGM wetlands parlance; Smith et al., 1995), in many instances it is more useful to represent a range of environmental conditions across a landscape. Classification of reference wetlands in the HGM approach harnesses wetland variability, and when integrated with the wetland classification scheme, provides a framework to characterize observed differences in wetland structure and function.

From 1993–2003, the Penn State Cooperative Wetlands Center (CWC) compiled a total of 222 reference wetlands across the five major ecoregions of Pennsylvania and spanning seven HGM subclasses. HGM subclasses were based on a regional classification system for Pennsylvania and adjoining ecoregions (Cole et al., 1997a,b; Brooks, 2004). The original intent for the reference set was to use reference data to improve the design and construction of restoration and creation projects, but aspects of the HGM approach were rapidly assimilated into the investigations of our reference wetlands to facilitate functional comparisons and condition assessments (Brooks, 2004; Brooks et al., 2004). We gleaned representative data used in this paper from this reference set and coupled it with comparable data from created wetlands (Bishel-Machung et al., 1996; Campbell, 1996; Cole and Brooks, 2000; Campbell et al., 2002) (Fig. 2). Riparian depressions are groundwater-supported sites with closed contours and a single outlet, usually located at the base of a hillslope near streams. Slopes have unidirectional flow along a topographic gradient, and are generally supported by a mixture of surface runoff and groundwater. Headwater floodplains are influenced by the overbank flooding regime of second order streams and by overland flow (Cole et al., 1997a,b).

Categorizing wetlands as degraded was based on a human disturbance score that combines landscape, buffer, and on-site stressors (Brooks et al., 2004). Observed stressors are compiled into general categories as described by Adamus and Brandt (1990) and Adamus et al. (2001). Wetlands in Pennsylvania are most often affected by hydrologic modifications, sedimentation, and alteration of natural vegetation.

We present the mean and S.D. for most variables, computed on a site basis, to indicate how degraded wetlands and created sites differ from reference standard wetlands. For most categories of HGM subclass and wetland type, the number of sites is low, so no statistical comparisons were attempted. Rather, our intent is to suggest trends worthy of further investigation, and to encourage use of reference site data to improve mitigation design, construction, and performance.

3. Results

Based on our collective work and a review of other selected papers, we believe hypotheses 1 and 2 can be accepted. In addition to offering supportive citations, we present selected data that supports both the degradation and the homogeneity aspects of the conceptual model.

3.1. Condition of reference wetlands along a disturbance gradient

Although land use patterns surrounding wetlands do not completely describe the level of observed disturbance or degradation found in wetlands, they are usually highly correlated (e.g., Wardrop and Brooks, 1998; O'Connell et al., 2000; Brooks et al., 2004). When wetlands are characterized during field studies, we have identified significant changes in wetland structure and function tied to stressors emanating from human-induced disturbances in the surrounding landscape. For the purposes of this paper, we have selected a few illustrative measures collected from 23 natural wetlands in three HGM subclasses; riparian depressions,

Table 1
Reference standard, degraded, and created wetlands studied in Pennsylvania

Site number	CWC number	CWC site name	County	HGM subclass	Years sampled (created)
1	5*	McCall Dam	Centre	Riparian depression	1993, 1994
2	6*	Sand Spring	Union	Riparian depression	1993, 1994
3	10*	Whipple Dam SP	Centre	Riparian depression	1993, 1994
4	13*	Clark's Trail	Union	Riparian depression	1993, 1994
5	18B	Buffalo Run	Centre	Riparian depression	1993, 1994
6	52	Tadpole	Centre	Riparian depression	1997
7	56	Farm 12	Centre	Riparian depression	1997
8	59	NBB–RD	Centre	Riparian depression	1997
9	1	BESP-PFO	Centre	Slope	1993, 1994
10	2	BESP-PFO	Centre	Slope	1993, 1994
11	14	LFC–PFO	Centre	Slope	1993, 1994
12	19*	Rothrock State Forest	Huntingdon	Slope	1993, 1994
13	24*	McGuire Rd	Huntingdon	Slope	1994
14	25	Windy Hill Farms	Centre	Slope	1994
15	54	Wardrop's	Centre	Slope	1994
16	55	Swamp White Oak	Centre	Slope	1997
17	4*	LFC Dam	Centre	Headwater floodplain	1993, 1994
18	18A	Buffalo Run	Centre	Headwater floodplain	1993, 1994
19	26	Water Authority	Centre	Headwater floodplain	1994
20	31	Cedar Run	Centre	Headwater floodplain	1994
21	53	NBB–HWF	Centre	Headwater floodplain	1997
22	57	Thompson Run	Centre	Headwater floodplain	1997
23	60	Laurel Run	Huntingdon	Headwater floodplain	1997
24	C1	Rt. 220A	Blair	Created	1995 (1993)
25	C2	Peterson Industrial Park A	Blair	Created	1995 (1992)
26	C5	Tipton	Blair	Created	1995 (1991)
27	C6	Snowshoe	Centre	Created	1995 (1990)
28	C7	Mt. Eagle	Centre	Created	1995 (Late 1980s)
29	C11	Sproul Interchange	Blair	Created	1995 (Late 1970s)
30	C12	Duncansville	Blair	Created	1995 (Late 1970s)

(*) Any site that is a reference standard.

slopes, and headwater floodplains (Cole et al., 1997b; Brooks, 2004) (Table 1). We provide examples from hydrologic, biogeochemical, and biodiversity functional categories, which typically are addressed in HGM assessment models (Smith et al., 1995) and indices of biological integrity (Karr and Chu, 1999).

We monitored water levels in reference wetlands and found that hydropatterns differed by HGM subclasses and changed with disturbance (Cole et al., 1997b) (Table 2). Sedimentation rates were significantly greater in disturbed sites compared with reference standards (Wardrop and Brooks, 1998). Morphological characteristics of soils differed as well; organic matter declined with disturbance and soil chroma suggested drier conditions prevailed in degraded sites (Campbell et al., 2002) (Table 2).

The CWC has conducted a number of studies addressing the response of various biological taxa to human induced disturbances. Field studies showed reduced richness in vascular plants and increases in the dominance of invasive plants (Campbell et al., 2002) (Table 2, Fig. 3). Greenhouse experiments designed to mimic stressors observed in the field suggest mechanisms that might be responsible for these trends. Walls et al. (2004) showed that sedimentation rates above expected amounts inhibit the germination and growth of riparian trees seedlings. Mahaney et al. (2004) found that sediment and nutrient stresses on herbaceous hydrophytes could alter plant community composition in favor of aggressive invasive species such as reed canarygrass (*Phalaris arundinacea*), which was comparable to findings by Green and Galatowitsch (2002) and Kercher and Zedler (2004). Wetland macroinvertebrate taxa were sampled in selected wetlands, and the data were compiled into a macroinvertebrate index of community integrity (ICI) (Bennett

Table 2
Selected data comparisons among reference, degraded, and created wetlands

Variable	Wetland type						
	Riparian depression, $n = 8$		Slope, $n = 8$		Headwater floodplain, $n = 7$		Created $n = 7$
	Reference	Degraded	Reference	Degraded	Reference	Degraded	
Hydrology							
Median depth (cm)	−10	+9	−23	−18	−15	−42	−8
Percent time root zone	81 ± 19	83 ± 20	66 ± 36	59 ± 19	91 ± 12	35 ± 20	78 ± 31
Percent time inundated	13 ± 11	77 ± 27	16 ± 17	3 ± 1	1 ± 1	5 ± 4	35 ± 26
Percent time dry	19 ± 19	18 ± 20	36 ± 35	41 ± 19	90 ± 56	58 ± 21	22 ± 31
Percent time saturated	68 ± 25	7 ± 8	49 ± 31	56 ± 20	53 ± 57	37 ± 18	42 ± 23
Soils							
Chroma (Munsell color)	1.1 ± 0.2	2.0 ± 0.1	1.5 ± 0.6	1.9 ± 0.5	1.2 ± 0.1	2.1 ± 0.5	2.3 ± 0.5
Percent organic matter	24 ± 9	9 ± 8	21 ± 13	8 ± 1	13 ± 2	6 ± 2	4 ± 1
Biodiversity							
Proportion of exotic and invasive plants	0 ± 0	0.35 ± 0.19	0.15 ± 0.19	0.40 ± 0.23	0.10 ± 0.14	0.48 ± 0.23	0.57 ± 0.24
Macroinvertebrate index of community integrity	31 ± 6	9 ± 2	33 ± 6	18 ± 3	NA	NA	20 ± 5
Bird community index	51 ± 23	39	57 ± 7	40 ± 6	NA	35 ± 5	NA

Median depth (cm)—median depth above (+) or below (−) ground level for all measurements taken in slotted wells; Percent time root zone—percent of total observations from slotted wells where water was within 30 cm of the ground surface; percent time inundated—percent of total observations from slotted wells where water was above the ground surface; percent time dry—percent of total observations from slotted wells where no water was recorded in slotted wells, regardless of absolute depth; percent time saturated—percent of total observations from slotted wells where water was recorded in slotted wells within 10 cm of the ground surface; chroma (Munsell color)—color recorded from Munsell Color chart, calculated as a mean value per wetland; percent organic matter—determined as loss on ignition of oven-dried samples at 450 °C (Storer, 1984); proportion of exotic and invasive plants—proportion of exotic and invasive vascular plant species in the most dominant species per wetland (Brooks, 2004); macroinvertebrate index of community integrity—based on multi-metric index (score range of 5–45) developed by Bennett (1999); bird community index—based on multi-metric index (score range of 20–77) developed by O'Connell et al., (2000); NA—indicates that data were not available.

and Brooks, unpublished). ICI scores were lower for disturbed wetlands and created sites. Similarly, songbirds were sampled across the wetland disturbance gradient, encompassing the surrounding landscape, and assembled into a bird community index (BCI) (O'Connell et al., 2000). BCI scores were based on bird guilds that were generated independently from wetland or landscape characteristics. Degraded wetlands had lower BCI scores than reference standard sites (Table 2). Created wetlands were not sampled for birds.

3.2. *Reference wetlands versus created wetlands*

During previous CWC research projects, selected reference wetlands were compared to several populations of wetland mitigation sites (Bishel-Machung et al., 1996; Campbell, 1996; Cole and Brooks, 2000; Campbell et al., 2002). We selected seven created wetlands where sufficient data were available to compare to the aforementioned 23 natural wetlands (Table 1).

Mitigation sites had higher amounts of sand and gravel, and lower amounts of organic matter, silt, and clay. Wetland mitigation sites contained more large particles in soils than reference wetlands. The presence of large amounts of large particles reflects construction practices that may involve excavation by blasting, or removal of upper layers of soil. Soil bulk density was higher in mitigation sites, again, a reflection of construction practices (compaction by machinery). Bulk density was inversely correlated with organic matter content. Soil matrix chroma, used as an indicator of the extent of soil saturation, was also higher than in reference wetlands, indicating that the imposed hydrologic regimes of created wetlands were insufficient to generate saturated or inundated conditions, which would facilitate iron reduction leading to greyer colors (Table 2). High chromas also reflect low levels of organic matter,

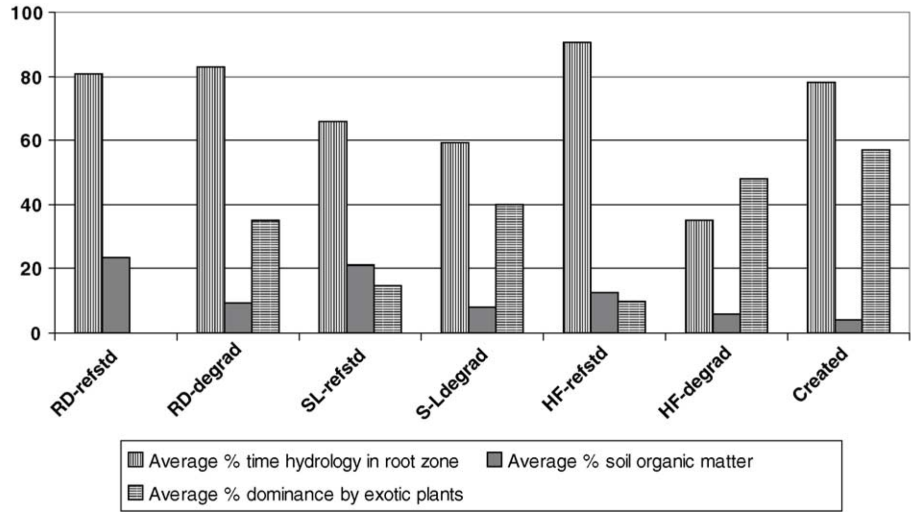

Fig. 3. Comparisons among wetland variables (percent time water in root zone, percent organic matter in soil, proportional dominance of exotic and invasive plant species) for reference standard (RefStd), degraded (Degrad) and created (Created) wetlands from three hydrogeomorphic subclasses; riparian depression (RD), slope (SL), and headwater floodplain (HF).

which normally functions as a substrate for reducing bacteria.

Campbell et al. (2002) found that created wetlands were more similar to degraded natural wetlands, than reference standard wetlands. These created sites ranged in age from 1–18 years since construction, thus, questions about lag times or evolution of restoration and creation technology were partially answered. The small amounts of organic matter found in mitigation sites could simply be due to project age, since accretion rates are slow and none of the mitigation sites were older than approximately 18 years at the time of the study. Created wetlands >10 years of age has significantly more organic matter than sites <10 years of age, although both had significantly less organic matter than reference standard or degraded wetlands (Campbell et al., 2002). Whether this age-based difference was due either to differences in time of construction or construction techniques is not known. It does not appear, however, that organic matter will accumulate within a decade to levels typical of natural wetlands. Average amounts of organic matter were >10% for the reference standard sites in the three subclasses of natural wetlands studied, whereas both degraded and created wetlands averaged <10% (Table 2, Fig. 3).

Vascular plant richness and total cover were both greater in reference versus created wetlands (Campbell et al., 2002). The proportion of dominant plants that were invasive was substantially greater in created wetlands, when compared with both reference standard and disturbed natural wetlands (Table 2, Fig. 3). Reference wetlands had a more complex perimeter to area relationship than in mitigation sites, indicating that there is a tendency to create regular, geometric shapes during the wetland construction because they are less expensive and are simpler to build (Campbell, 1996).

4. Discussion

In this paper, we provide evidence that regardless of original intent, wetland mitigation projects result in wetlands of moderate to low condition, that are in some ways, structurally and functionally equivalent to moderately and severely degraded natural wetlands. When compared to natural reference standard wetlands (e.g., Smith et al., 1995), or those approaching the best possible condition in a given region, creation projects emulate degraded wetlands in their soil characteristics and dominance by invasive plants. With regard to hydrology, created sites span a continuum from being too dry to be considered a jurisdictional wetland, to being inundated with water that is too deep to support emergent and woody plant communities typical of natural wetlands. Created wetlands that are excessively inundated become divergent from severely degraded wetlands as well. The end result in both cases is often a more homogeneous set of wetlands that does not resemble their original natural counterparts. The range of natural variability is missing in these two sets of wetlands; mitigation projects and degraded wetlands (Fig. 1).

As suggested by Sibbing (2003), fundamental changes in wetland mitigation policies and practices are needed to remedy this trend. If managers and practitioners truly intend to restore lost area and function that encompasses the full diversity of wetland types, then steps must be taken to improve the design and construction models that are currently in use. We propose that all restoration and creation projects be based on the structural and functional characteristics of natural reference standard wetlands of the same HGM and vegetation type for any given geographic region. Within this context, we refer to these specific characteristics as performance criteria, because ultimately, the same measures used to assess wetland conditions should be used in the design and construction process, and during evaluation of success. That is, at the conclusion of the project, does the wetland perform as intended? By using the same protocols throughout permitting, design, construction, and monitoring processes, restoration and creation projects are more likely to succeed in mimicking or at least replacing equivalent structures and functions found in wetlands of high ecological integrity for any given wetland type.

Based on these collective results, we developed the illustrative model (Fig. 1) that suggests how wetland diversity and variability often become more homogeneous when subjected to a set of stressors. There is a convergence of characteristics such that the end result is a population of wetlands that are relatively homogeneous. The original variability expressed as a set of heterogeneous measures from less disturbed natural wetlands has been lost. In addition, the soil characteristics and composition of biological communities of creation projects may mirror those of degraded wetlands. Hydrologically, created wetlands show wide variability in their hydrologic regimes, which can cause them to be either similar to degraded wetlands, or appear in a unique subclass of their own.

The implications are clear. The inherent heterogeneity of naturally occurring wetlands is lost as degradation progresses. Functions attributed to a diverse set of wetland types are necessarily reduced, resulting in lower species richness and changes in species composition across multiple taxa (e.g., vascular plants, macroinvertebrates, and birds). When these degraded wetlands are compared to created projects, they may be equivalent or form their own unique cluster. This indicates that there is room for considerable improvement in the design and construction of created wetlands, and probably restored wetlands, too. If these projects are structurally equivalent to degraded wetlands, then they undoubtedly provide comparable levels of function, and possibly fewer numbers of functions.

The conceptual model we propose suggests three, intertwined courses of action for managers and practitioners. All three rely heavily on the use of reference standard wetlands as design templates for protection, restoration, and creation projects. (1) We should focus our attention not only on losses of wetland area, but also losses of functions. This suggests a need for greater protection of existing wetlands of relatively high ecological integrity to avoid further loss of function through degradation. Once degraded, however, these wetlands offer abundant opportunities for restoration provided that the stressors causing the degradation can be reduce or eliminated. (2) When creation of a wetland becomes the selected option, design and construction specifications should be guided by data provided by reference standard wetlands of the appropriate type (e.g., HGM subclass). Using reference site data to guide the design and construction of these projects ensures that the appropriate endpoints are selected, and over time, hopefully achieved. (3) By using the same sampling protocols for monitoring sites throughout the assessment and evaluation phases, direct measures of success can be obtained, and the chances of constructing sustainable wetland projects of the desired type are greatly enhanced.

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